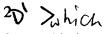1   1.   **REFERENCES**

which

3   ~~This~~ is a continuation-in-part application of U.S. Patent Application, serial number

now U.S. Patent No. 5,504,603,

4   223,251, filed April 4, 1994, entitled "Optical Compensator for Improved Gray Scale

5   Performance in Liquid Crystal Display."

6

7   2.   **BACKGROUND OF THE INVENTION**

8

9   This invention is concerned with the design of liquid crystal displays (LCDs)

10   and, more particularly, with techniques for maximizing the field of view of such

11   displays by maintaining a high contrast ratio and minimal variance in relative gray

12   levels over a wide range of viewing angles. These goals are achieved through the

13   fabrication and manufacture of LCDs using O-plate technology.

14

15   2.1 LCD Technology Overview

16

17   Liquid crystals are useful for electronic displays because polarized light

18   traveling through a liquid crystal layer is affected by the layer's birefringence, which

19   can be changed by the application of a voltage across the layer. By using this effect,

20   the transmission or reflection of light from an external source, including ambient

21   light, can be controlled with much less power than is required for the luminescent

22   materials used in other types of displays. As a result, liquid crystal displays are now

23   commonly used in a wide variety of applications, such as, for example, digital

24   watches, calculators, portable computers, and many other types of electronic equip-

25   ment. These applications highlight some of the advantages of LCD technology in-

26   cluding very long operational life in combination with very low weight and low power

27   consumption.

28

1   The information content in many liquid crystal displays is presented in the

2   form of multiple rows of numerals or characters, which are generated by segmented

3   electrodes deposited in a pattern on the display. The electrode segments are

4   connected by individual leads to electronic driving circuitry. By applying a voltage to

5   the appropriate combination of segments, the electronic driving circuitry controls the

6   light transmitted through the segments.

7

8   Graphic and television displays may be achieved by employing a matrix of

9   pixels in the display which are energized by an X-Y sequential addressing scheme

10   between two sets of perpendicular conductors. More advanced addressing schemes,

11   applied predominantly to twisted nematic liquid crystal displays, use arrays of thin

12   film transistors to control driving voltages at the individual pixels.

13

14   Contrast and stability of relative gray scale intensities are important attributes

15   in determining the quality of a liquid crystal display. The primary factor limiting the

16   contrast achievable in a liquid crystal display is the amount of light which leaks

17   through the display in the dark state. In addition, the contrast ratio of the liquid

18   crystal device also depends on the viewing angle. The contrast ratio in a typical

19   liquid crystal display is a maximum only within a narrow viewing angle centered near

20   normal incidence and drops off as the angle of view is increased. This loss of

21   contrast ratio is caused by light leaking through the black state pixel elements at large

22   viewing angles. In color liquid crystal displays, such leakage also causes severe color

23   shifts for both saturated and gray scale colors.

24

25   The viewing zone of acceptable gray scale stability in a typical prior art

26   twisted nematic liquid crystal display is severely limited because, in addition to color

27   shifts caused by dark state leakage, the optical anisotropy of the liquid crystal

28   molecules results in large variations in gray level transmission, i.e., a shift in the

1 brightness-voltage curve, as a function of viewing angle. The variation is often

2 severe enough that, at extreme vertical angles, some of the gray levels reverse their

3 transmission levels. These limitations are particularly important for applications

4 requiring a very high quality display, such as in avionics, where viewing of cockpit

5 displays from both pilot and copilot seating positions is important. Such high

6 information content displays require that the relative gray level transmission be as

7 invariant as possible with respect to viewing angle. It would be a significant

8 improvement in the art to provide a liquid crystal display capable of presenting a high

9 quality, high contrast image over a wide field of view.

10

11 Figures 1a and 1b show a conventional normally, white, twisted nematic liquid

12 crystal display 100 including a polarizer 105 and an analyzer 110. The polarizer 105

13 and the analyzer 110 are each bonded to glass substrates (not shown), such that the

14 polarization axis of the analyzer 110 is perpendicular to that of the polarizer 105. The

15 figures also show a light source 130 and a viewer 135.

16

17 An area between the polarizer 105 and the analyzer 110 contains a nematic

18 liquid crystal material. The nematic phase is a fluid state of matter whose constituent

19 molecules show long range correlation of their angular orientation (they are contained

20 to have their long axes generally be parallel to one another), but no long range

21 correlation of their positions in space as would be the case in a crystalline solid. The

22 average orientation of the nematic molecules' long axes at any point in the material is

23 called the director.

24

25 In the normally white configuration of Figures 1a and 1b, a "nonselect" area

26 115 (no applied voltage) appears light, while a "select" area 120 (those which are

27 energized by an applied voltage) appear dark. In the nonselect area 115 the liquid

28 crystal molecules are constrained to adopt the helical structure shown in the figure

1   with their molecular long axes parallel to the glass substrates. In the select area **120**

2   the liquid crystal molecules tend to tilt and rotate toward alignment with the applied

3   electric field. The alignment state with the liquid crystal molecules' long axes normal

4   to the surfaces of the glass substrates is termed a homeotropic alignment. In practical

5   twisted nematic displays the applied electric fields are not strong enough to yield

6   completely homeotropic alignment.

7

8   Many of the materials discussed in this document are birefringent. That is to

9   say, they have varying indices of refraction depending on the direction of the electric

10   vector of the light propagating through the material. The index of refraction is the

11   ratio of the speed of light in a vacuum to that in the material. Materials such as

12   liquid crystals that have different optical properties along different axes are said to be

13   optically anisotropic. Materials without such angular variation are said to be

14   isotropic. A uniaxial optical material has only one axis, the extraordinary axis, along

15   which the electric vector of light interacts to yield a unique index of refraction (n_e).

16   This index will either be the highest or lowest found in the material. In a uniaxial

17   material all possible axes perpendicular to the extraordinary axis will yield the same

18   index of refraction (called the ordinary index, n_o) for light whose electric vector lies

19   in those directions; the material has ellipsoidal symmetry. If the extraordinary axis

20   has the highest associated refractive index value of any axis the material is said to be

21   positively birefringent. If it has the lowest refractive index, the material is said to be

22   negatively birefringent. Light traversing a material such that its electric vector has

23   components along both ordinary and extraordinary axes will have one polarized

24   component retarded in its velocity as compared to the other. If a material has a

25   unique axis which is associated with the highest refractive index, but the axes

26   perpendicular to it have associated refractive indices which differ one to the other, the

27   material is said to be optically biaxial and we will refer to the axis with the associated

28   highest index as the principal optic axis. In this document the term "optical symmetry

1   axis" will be defined to mean the extraordinary axis in uniaxial materials and the

2   principal optic axis in biaxial materials.

3

4   Because the liquid crystals used for twisted nematic displays exhibit positive

5   birefringence, the homeotropic alignment state would exhibit the optical symmetry of

6   a positively birefringent C-plate. As is well known in the art, a C-plate is a uniaxial

7   birefringent plate with its extraordinary axis (i.e., its optic or c-axis) perpendicular to

8   the surface of the plate (parallel to the direction of normally incident light). In the

9   select state, the liquid crystal in a normally white display would thus appear isotropic

10   to normally incident light, which would be blocked by the crossed polarizers.

11

12   One reason for the loss of contrast with increased viewing angle which occurs

13   in a normally white display is that a homeotropic liquid crystal layer will not appear

14   isotropic to off-normal light. Light propagating through the layer at off-normal angles

15   appears in two modes due to the birefringence of the layer; a phase delay is intro-

16   duced between those modes and increases with the incident angle of the light. This

17   phase dependence on incidence angle introduces an ellipticity to the polarization state

18   which is incompletely extinguished by the second polarizer, giving rise to light

19   leakage. To correct for this effect, an optical compensating element must also have

20   C-plate symmetry, but with negative birefringence ($n_e < n_o$). Such a compensator

21   will introduce a phase delay opposite in sign to the phase delay caused by the liquid

22   crystal layer, thereby restoring the original polarization state and allowing light

23   passing through energized areas of the layer to be blocked more completely by the

24   output polarizer. C-plate compensation, however, does not impact the variation of

25   gray scale with viewing angle, which is addressed by the present invention.

26

27   Figure 2 depicts the coordinate system which is used to describe the

28   orientation of both liquid crystal and birefringent compensator optic axes. Light

1 propagates toward the viewer **200** in the positive z direction **205** which, together with

2 the x-axis **210** and the y-axis **215**, form a right-handed coordinate system.

3 Backlighting is provided, as indicated by the arrows **220**, from the negative z

4 direction. The polar tilt angle Θ **225** is defined as the angle between the liquid crystal

5 optic axis $\hat{C}$ **230** and the x-y plane, measured from the x-y plane. The azimuthal or

6 twist angle Φ **235** is measured from the x-axis to the projection **240** of the optic axis

7 onto the x-y plane.

8

9 ## 2.2 Normally White Twisted Nematic LCDs

10

11 Figure 3 is a cross-sectional schematic view of a prior art twisted nematic,

12 transmissive type normally white liquid crystal display. The display includes a

13 polarizer layer **300** and an analyzer layer **305**, between which is positioned a liquid

14 crystal layer **310**, consisting of a liquid crystal material in the nematic phase.

15

16 It is convenient in describing the orientation of various compensation elements

17 of the display to refer to a normal axis perpendicular to the display, which is depicted

18 by a dashed line **370**. In the case of a normally white display, the polarizer **300**

19 (with a polarization direction in the plane of the drawing **315**) and the analyzer **305**

20 (with a polarization direction into the plane of the drawing **320**) are oriented with

21 their polarization directions at 90° to one another. (A polarizer **300** and an analyzer

22 **305** both polarize electromagnetic fields. Typically, however, the term 'polarizer'

23 refers to a polarizer element that is closest the source of light while the term

24 'analyzer' refers to a polarizer element that is closest the viewer of the LCD.) The

25 liquid crystal layer **310** is sandwiched between a pair of glass plates or substrates **340**

26 and **345**. A first transparent electrode **325** and a second transparent electrode **330** are

27 positioned on the glass substrates **340** and **345** adjacent to opposite surfaces of the

28 liquid crystal layer **310** so that a voltage can be applied, by means of a voltage source

1   335, across the liquid crystal layer. As is explained below, the inner surfaces **346**

2   and **347** of the glass plates **340** and **345** and the transparent electrodes **325** and **330**,

3   which are proximate to the liquid crystal layer **310**, can be physically or chemically

4   treated to effect the desired liquid crystal orientation.

5

6   As is well known in the LCD art (see, e.g., Kahn, The Molecular Physics of

7   Liquid – Crystal Devices, Physics Today, Page 68, 1982), when the inner surfaces

8   **346** and **347** of the plates **340** and **345** are coated with a surface treatment for aligning

9   the liquid crystal such as polyamide, buffed, and oriented with their buffed directions

10 perpendicular, the director of the liquid crystal material, absent any applied electrical

11 voltage, will tend to align with the buffed direction (known as the "rub direction") in

12 the regions of the layer **310** proximate each of the plates **340** and **345**. Furthermore,

13 the director will twist smoothly with respect to the normal axis through an angle of

14 90° along a path in the layer **310** from the first major surface adjacent to the plate

15 **340** (i.e., at the **310/340** interface) to the second major surface adjacent to the plate

16 **345** (i.e., at the **310/345** interface).

17

18   In the absence of an applied electric field, the direction of polarization of

19 incoming polarized light will be rotated by 90° in traveling through the liquid crystal

20 layer **310**. When the glass plates and the liquid crystal layer are placed between

21 crossed polarizers, such as the polarizer **300** and the analyzer **305**, light polarized by

22 the polarizer and traversing the display, as exemplified by the light ray **350**, will thus

23 be aligned with the polarization direction of the analyzer **320** and therefore will pass

24 through the analyzer **305**.

25

26   When a sufficient voltage is applied to the electrodes **325** and **330**, however,

27 the applied electric field causes the director of the liquid crystal material to tend to

28 align parallel to the field. With the liquid crystal material in this state, light passed

1   by the polarizer **300**, as illustrated by the light ray **355**, will be extinguished by the

2   analyzer **305**. Thus, an energized pair of electrodes will produce a dark region in the

3   display, while light passing through regions of the display which are not subject to an

4   applied field will produce illuminated regions. As is well known in the LCD display

5   art, an appropriate pattern of electrodes, activated in selected combinations, can be

6   utilized in this manner to display alphanumeric or graphic information. As explained

7   further below, one or more compensator layers, such as the layers **360** and **365**, may

8   be included in the display to improve the quality of the display.

9

10 ## 2.3 Normally White Twisted Nematic LCD Characteristics

11

12   Figure 4 shows a calculated plot of liquid crystal director tilt as a function of

13 position in a liquid crystal layer (where the cell gap has been normalized to unity) in

14 a 90° twisted nematic cell. Typical distributions for molecular tilt angles when no

15 voltage is applied (curve **400**), under a typical select state voltage (curve **405**), and

16 under the application of several intermediate voltages chosen to yield linearly spaced

17 gray levels (curves **410, 415, 420, 425, 430,** and **435**) are shown.

18

19   Figure 5 is a related plot for the same cell depicting the calculated twist angle

20 (the azimuthal angle Φ of the molecular long axes given an initial rub angle azimuth

21 of 45°) of the liquid crystal molecules as a function of position in the cell. When

22 there is no applied voltage, the twist is distributed evenly throughout the cell (straight

23 line curve **500**). Under a fully select state voltage, the twist angles are distributed as

24 shown by the external, S-shaped curve **505**. The twist distributions for gray levels

25 are shown by the intermediate curves between the two curves **500** and **505**.

26

27   As illustrated by Figures 4 and 5, when the fully selected voltage is applied,

28 nearly all of the change in twist angle experienced by the liquid crystal molecules and

1   little of the change in tilt angle occurs in the central region of the cell. Because of

2   this phenomena, the continuous variation of molecular orientation within the cell can

3   be separated into three regions, each of which is characterized by its own optical

4   symmetry. Thus, the central regions **440** (Figure 4) and **510** (Figure 5) can be

5   considered as nominally homeotropic in the fully selected state, approximating the

6   properties of a C-plate. The regions **445** and **450** (Figure 4) and **515** and **520** (Figure

7   5), near each surface of the cell, behave as A-plates, each with its extraordinary axis

8   aligned with the rub direction of the proximate substrate. Because there is essentially

9   no twist in the molecules in the regions **445**, **450**, **515**, and **520**, the molecules are

10   essentially aligned with the respective rub directions on either side of the liquid

11   crystal layer. In addition, because the twist angle of the molecules in the regions **445**

12   and **515** tends to be perpendicular to the twist angle of the molecules in the regions

13   **450** and **520**, the effect of these two regions on light traveling through the cell tends

14   to be canceled, leaving the middle C-plate region to exert the dominant influence.

15

16   2.3(a)   C-Plate Compensation

17

18   As is well known in the art, a negative C-plate compensator is designed to

19   correct for the angle dependent phase shift introduced by propagation through the

20   central, approximately C-plate region of a LCD cell. Such a compensator is effective

21   to the extent that the optical symmetry of the central region dominates the selected

22   state of the liquid crystal cell, that is, the extent to which the molecules align with the

23   applied field. This implies that negative C-plate compensation will work best when

24   strong fields are used for the energized state as this makes the homeotropic

25   approximation more nearly correct. The use of a C-plate has been demonstrated to

26   significantly reduce the leakage of the dark state over an extended field of view, thus

27   improving contrast and reducing color desaturation.

28

1   2.3(b)   Gray Scale Stability

2

3   While the C-plate compensator may be used to improve contrast it does not

4   improve grayscale stability. The problem of maintaining constant grayscale

5   luminance differences over the field of view relates substantially to the brightness

6   level changes for levels assigned between the select (black for a normally white

7   display) and nonselect (white for a normally white display) states. This phenomenon

8   is generally depicted using transmission, or brightness versus voltage (BV)

9   electrooptic response curves for a display to which eight gray levels are assigned,

10   from level 0 (the select black state) to level 7 (the nonselect white state). Gray levels

11   between 0 and 7 are chosen by assigning them a set of voltages spaced linearly in

12   brightness along the BV curve between the select and nonselect voltages.

13

14   Figure 6 is a plot of calculated BV curves for a normally white, 90° twisted

15   nematic display as the horizontal viewing angle varies from 0° to 40° in 10°

16   increments while the vertical viewing angle remains fixed at 0°. (The change in the

17   BV curves with horizontal angle is first order independent of whether the horizontal

18   deviation is to the left or right.) Note that the regions of each curve over which gray

19   levels would be selected almost overlie one another for the various horizontal angles.

20   This means that gray levels chosen to be linearly spaced at zero degrees would remain

21   very nearly linear at even high horizontal viewing angles.

22

23   The gray scale linearity problem appears most predominantly when the vertical

24   viewing angle varies. This is illustrated in Figure 7, which shows a series of BV

25   curves for a normally white, 90° twisted nematic display as the vertical viewing angle

26   varies from -10° to +30° while the horizontal viewing angle remains fixed at 0°. It

27   can be observed that for angles below 0° (measured from the normal) the BV curves

1 shift to the right (higher voltage), and fall monotonically from their maximum but fail

2 to reach zero.

3

4 For angles above normal, the curves shift to the left and develop a rebound

5 after an initial minimum. These effects can be explained by considering the

6 perspectives of viewers looking at the display from above, at, and below normal, as

7 shown in Figure 8. The critical feature to note is the relationship between the light

8 traveling towards the viewer and the average liquid crystal director tilt at the center of

9 a cell as voltage across the cell is increased.

10

11 For instance, as the voltage across a cell is increased, the average liquid

12 crystal director in the center of the cell tilts from a parallel (with respect to the

13 polarizer **300** and analyzer **305**) orientation **815** toward a homeotropic one **825**. For

14 the viewer at normal incidence **800**, retardation is highest at the nonselect state

15 voltage and lowest at the select state voltage. When the anisotropy is zero, the

16 polarization state of the light is unchanged and it is blocked by the analyzer. Thus,

17 the viewer sees a monotonic decrease in brightness to zero with increasing voltage.

18

19 Now consider the case of a positive vertical viewing direction (viewer above

20 normal incidence **805**). At some intermediate voltage the average director **820** points

21 toward the viewer and the retardation is minimal. Here the viewer sees a brightness

22 with voltage that initially decreases toward a minimum, at the point of minimal retar-

23 dation, and then increases.

24

25 For the negative vertical viewing direction (viewer below normal incidence

26 **810**), the average director always presents a large anisotropy to a light ray, even at

27 the highest voltage. The viewer therefore sees a monotonic decrease in brightness.

28 Furthermore, the average liquid crystal director is always oriented at a larger angle

1   with respect to the light ray for the below normal viewer **810** than it is for the normal

2   incidence viewer **800**. Therefore, the anisotropy is greater and the brightness level is

3   always higher in the negative vertical viewing direction than it is at normal incidence.

4

5   This dependency, of an LCD's brightness versus viewing angle, has a

6   profound impact on gray scale linearity. (Note that a voltage chosen to yield a 50%

7   gray level on the 0° curve in Figure 7 yields a dark state on the +30° curve and

8   approaches a fully white state at -10°.)

9

10   2.3(c)   O-Plate Gray Scale Compensation

11

12   To eliminate reversal of gray levels and improve gray scale stability, a

13   birefringent O-plate compensator can be used. The O-plate compensator principle, as

14   described in pending U.S. Patent Application Serial No. 223,251 filed on April 4,

15   1994 utilizes a positive birefringent material with its principal optic axis oriented at a

16   substantially oblique angle with respect to the plane of the display (hence the term

17   "O-plate"). "Substantially oblique" implies an angle appreciably greater than 0° and

18   less than 90°. O-plates have been utilized, for example, with angles relative to the

19   plane of the display between 35° and 55°, typically at 45°. Moreover, O-plates with

20   either uniaxial or biaxial materials can be used. O-plate compensators can be placed

21   in a variety of locations between a LCD's polarizer layer and analyzer layer.

22

23   In general, O-plate compensators may also include A-plates and/or negative C-

24   plates as well as O-plates. As is well known in the art, an A-plate is a birefringent

25   layer with its extraordinary axis (i.e., its c-axis) oriented parallel to the surface of the

26   layer. Its a-axis is thus oriented normal to the surface (parallel to the direction of

27   normally incident light), leading to its designation as an A-plate. A-plates may be

1 fabricated by the use of uniaxially stretched polymer films, such as polyvinyl alcohol,

2 or other suitably oriented organic birefringent materials.

3

4   A C-plate is a uniaxial birefringent layer with its extraordinary axis oriented

5 perpendicular to the surface of the layer (parallel to the direction of normally incident

6 light). Negatively birefringent C-plates may be fabricated by the use of uniaxially

7 compressed polymers (See, e.g., Clerc, U.S. Patent No. 4,701,028), stretched poly-

8 mer films, or by the use of physical vapor deposited inorganic thin films (See, e.g.,

9 Yeh, U.S. Patent No. 5,196,953), for example.

10

11   Oblique deposition of a thin film by physical vapor deposition is known to

12 produce a film having birefringent properties (see, e.g. Motohiro, Applied Optics,

13 Volume 28, Pages 2466 - 2482, 1989). By further exploiting the tilted orientation of

14 the optical symmetry axis, this process can be used to fabricate O-plates. Such

15 components are by their nature biaxial. Their growth characteristics generate a

16 microscopic columnar structure. The angles of the columns are tipped towards the

17 direction of the arriving vapor stream. A deposition angle (measured from normal) of

18 76°, for example, results in a column angle of approximately 45°. The columns

19 develop an elliptical cross-section as the result of shadowing. This elliptical cross-

20 section gives rise to the biaxial character of the films. The birefringence, in

21 magnitude and symmetry, is entirely attributable to the film microstructure and is

22 referred to as form birefringence. These phenomena in thin films have been

23 extensively studied and described by Macleod (Structure-related Optical Properties of

24 Thin Films, J. Vac. Sci. Technol. A, Volume 4, No. 3, Pages 418-422, 1986).

25

26   Uniaxial O-plate components can also be used to improve grayscale stability in

27 normally white twisted nematic LCDs. These may be fabricated by the use of

1 suitably oriented organic birefringent materials. Those skilled in the art will

2 recognize other means for fabricating both uniaxial and biaxial O-plates.

3

4   Figures 9 and 10 show the effect that an O-plate compensator can have on

5 normally white twisted nematic display. Figure 9 shows the BV curves for a

6 normally white twisted nematic display using an O-plate compensator at a fixed

7 vertical viewing angle of 0° and various horizontal viewing angles. Figure 10 shows

8 the BV curves for a normally white twisted nematic display using an O-plate

9 compensator at a fixed horizontal viewing angle of 0° and various vertical viewing

10 angles. In this example, the O-plate layer is positioned adjacent to the liquid crystal

11 layer on the source side of the display. A-plate layers are disposed on both sides of

12 the O-plate/liquid crystal layer stack. The variation of the BV curves versus both

13 horizontal and vertical viewing angles is greatly reduced relative to the

14 uncompensated case shown in Figures 6 and 7.

15

16   Elimination of gray scale reversal by the use of an O-plate compensator layer

17 occurs in the following manner. In the positive vertical viewing direction, the

18 retardation of the O-plate increases with viewing angle and tends to offset the

19 decreasing retardation of the liquid crystal layer. When the viewer is looking down

20 the axis of the average liquid crystal director, the presence of the O-plate prevents the

21 layers between the two polarizers from appearing isotropic. Thus, the rebound in the

22 BV curve, shown in Figure 7, is reduced and moved to higher voltages outside of the

23 gray scale voltage range as shown in Figure 10.

24

25   In the negative vertical viewing direction, the combination of an O-plate and

26 an A-plate with their optic axes nominally at right angles tends to exhibit

27 birefringence characteristics similar to that of a negative birefringence retarder with

28 its optic axis oriented perpendicular to the plane containing the axes of the O-plate

1   and A-plate. The direction of this retarder axis is nominally parallel to the orientation

2   of the average liquid crystal in the central region of the cell when it is driven at a

3   voltage between select and nonselect states. Thus, the presence of an O-plate oriented

4   in this manner tends to cancel the birefringence of the liquid crystal layer, pulling the

5   BV curve down, or equivalently, moving it toward the direction of lower voltages

6   (i.e., left) as shown in Figure 10. A similar effect occurs in the positive and negative

7   horizontal viewing directions as shown in Figure 9 when compared to Figure 6.

8

9   The overall effect of introducing an O-plate compensator in this manner is to

10   eliminate large rebounds in the gray scale voltage region and reduce the left-to-right

11   shift in the BV curves as the viewing angle is varied from negative to positive vertical

12   angles.

13

14   The orientations of the compensator optic axes can be carefully chosen so that

15   the combined retardation effects cancel each other in the normal incidence viewing

16   direction as well as minimize rebounds in the horizontal viewing direction.

17   Combinations of more than one O-plate can be used as long as their orientations

18   satisfy these requirements. Furthermore, negative C-plates can, for certain

19   configurations, increase the contrast ratio at large fields of view, occasionally with

20   some decrease in gray scale linearity.

21

22   2.3(d)   O-Plate Technology

23

24   The liquid crystal layer, the compensator layer(s), the polarizer layer, and the

25   analyzer layer can assume a variety of orientations relative to one another in a liquid

26   crystal display. Some of the possible configurations which have been considered, and

27   set out in pending U.S. Patent Application No. 223,251 are repeated in Table 1;

28   where 'A' represents an A-plate, 'C' represents a C-plate, 'O' represents an O-

1 plate, 'LC' represents the liquid crystal, and 'OxO' represents crossed O-plates.

2 Crossed O-plates are adjacent O-plates with their azimuthal angles Φ **235** nominally

3 crossed, one oriented between 0° and 90°; and the second oriented between 90° and

4 180°.

Table 1. Liquid Crystal Display Elements

← Toward Rear (Polarizer Side)					Toward Front (Analyzer Side) →		
		O	A	LC			
		A	O	LC			
			O	LC	O	A	
	A	O	A	LC			
		O	A	LC	A		
	O	A	C	LC			
		OxO	A	LC			
	A	OxO	A	LC			
			A	LC	OxO	A	
A	O	A	C	LC			
			A	LC	O	A	
	A	O	C	LC	C	O	
	A	O	C	LC	C	O	A
	C	A	O	LC	O	A	C

24 The projections of the principal axes onto the plane of the display with respect

25 to the liquid crystal director can vary with the embodiment. In some cases, for

26 example with two O-plates, the O-plate axis projections are at 45° with respect to the

27 average liquid crystal director, while in others, the O-plate axis is parallel with the

28 liquid crystal director.

29 Crossed O-plate (OxO) designs that are further compensated with A-plates

30 provide additional design flexibility. The choice of A-plate value is not critical as

1 such designs can be adjusted by varying the relative orientations of the A-plates.

2 Thus, it is possible to generate desired solutions with commercially available A-plate

3 retardation values.

4

5 ## 2.4   Twisted and Splayed O-plates

6

7 Computer modeling and display cell measurements show the optical behavior

8 of the biaxial O-plate based compensators produced from Ta_2O_5 to be qualitatively

9 different from that of compensators produced from uniaxial polymerized liquid crystal

10 materials. For some applications, grayscale stability and contrast over field of view

11 properties produced by the biaxial components are preferred. However, organic

12 compensator films based on uniaxial liquid crystal polymers are very attractive

13 because they both make a wider range of material parameters accessible and also

14 allow the possibility of inexpensive mass production of compensator components.

15 Therefore a goal of further compensator development has been to produce a thin film

16 organic O-plate layer which shows biaxial character.

17

18 It is believed that biaxial compensator components produce qualitatively

19 different optical performance because the deformation structure of the partially

20 selected liquid crystal layer in a twisted nematic display has some biaxial character

21 itself. In the nonselect state the liquid crystal has a helical structure which rotates the

22 polarization state of incident light by means of the process of adiabatic waveguiding

23 as described above. As the electric field across the liquid crystal layer is increased

24 the helical structure is distorted and the efficiency of the waveguide decreases. Some

25 portion of the light is no longer efficiently rotated and begins as a result to lag the

26 rotation of the liquid crystal helical structure. This light encounters a medium

27 intermediate in refractive index between the ordinary and extraordinary index values.

28 The net result is that the medium appears biaxial.

1   The O-plate solution to the compensation of the twisted nematic display was

2   based on the approximate model described above that the liquid crystal layer in the

3   select state of the twisted nematic display could be divided into three regions, two A-

4   plate-like regions and a central region of pseudo-homeotropic character. O-plate

5   compensated displays, however, operate with the full-on black state accessible at

6   voltages considerably reduced from the black state voltage in uncompensated displays.

7   At these reduced drive voltages, the liquid crystal layer central region is unlikely to

8   have completely deformed to the pseudo-homeotropic state, and the three region

9   model becomes even more approximate. At these intermediate voltages the liquid

10   crystal layer central region will still be significantly splayed and twisted yielding the

11   biaxial character described in the above paragraph.

12

13   The intuitive approach to compensator development has been that like

14   compensates like, i.e., compensators should have similar or complementary optical

15   symmetries to the liquid crystal layers they are intended to compensate. Based on this

16   idea and the analysis in the above paragraphs it was decided to investigate splayed and

17   twisted O-plate structures with the idea that they could be substituted into the existing

18   O-plate configurations described above with resulting improved performance.

19

20   2.5   Summary

21

22   When viewed at an angles nearly normal to their surfaces twisted nematic

23   liquid crystal displays provide high quality optical characteristics, but at large viewing

24   angles the image tends to degrade and exhibit poor contrast and grayscale stability.

25   Compensator configurations containing O-plates have been shown to produce greatly

26   improved contrast and grayscale stability over field of view. O-plate configurations

27   with biaxial optical symmetry have given qualitatively different performance than

28   those with uniaxial symmetry. It is believed that this is true because biaxial O-plates

1 more closely approximate the symmetry of an energized twisted nematic liquid crystal

2 layer. Currently available biaxial O-plates are produced using an expensive vacuum

3 deposition process, and a more cost effective large volume process is desired.

4

5   It is the goal of this invention to provide a process for producing O-plates

6 which have the desired biaxial symmetry using an inexpensive fabrication process

7 which is capable of being scaled up to large volume production.

8

9 **3.   SUMMARY OF THE INVENTION**

10

11   The compensator design of this invention, which includes a positively

12 birefringent twisted and/or splayed O-plate layer, makes possible a significant

13 improvement in the gray scale properties and contrast ratios of liquid crystal displays

14 (LCDs) over a wide range of viewing angles. By making use of polymerized thin

15 films of organic liquid crystal materials the compensators are able to duplicate the

16 performance of existing biaxial inorganic O-plate compensators, but at reduced cost

17 and with more design flexibility.

18

19   An O-plate compensator comprising an organic liquid crystal polymer thin

20 film, and methods for fabricating the same, are disclosed. On the microscopic scale

21 the film is composed of a polymerized birefringent liquid crystal material which is

22 uniaxial or near uniaxial in character. The liquid crystal material is constrained such

23 that its optical symmetry axis is, on average, oriented obliquely with the surface of

24 the film. Within this constraint, the direction of the material's optical symmetry axis

25 is allowed to vary continuously along the axis normal to the film surface. If the

26 variation is in the tilt angle of the optical symmetry axis relative to the film surface

27 the liquid crystal material will have splayed structure. If the variation is in the

1   azimuthal angle of the optical symmetry axis the material will have twisted structure.

2   The invention can comprise either angular variation or both in combination.

3   The oblique orientation of the liquid crystal director, which is parallel to the

4   optical symmetry axis, is achieved by casting an organic thin film onto a surface

5   specially prepared for orienting liquid crystal monomers, such as oblique SiO,

6   mechanically rubbed polymers, etc. The variation in tilt angle through the layer is

7   achieved by selecting a liquid crystalline material such that its tilt angle at the

8   substrate surface is substantially different from that at the liquid crystal air interface.

9   The variation in azimuthal angle through the layer is achieved by doping the liquid

10   crystal monomer with a chiral additive in sufficient quantity so as to provide the

11   proper helical pitch along the axis normal to the film surface. The film can either be

12   cast from a solution of the liquid crystal polymer or from a reactive liquid crystal

13   monomer. Any solvent that may be used during the fabrication process is evaporated

14   off and the organic thin film is annealed at a temperature in its nematic phase. If a

15   reactive monomer is used, the film is then photopolymerized. Finally, the film is

16   thermally quenched to 'freeze' in the liquid crystalline structure. Alternative

17   embodiments of the splayed / twisted O-plate include the use of nematic or smectic C

18   materials. Fabrication techniques employing these materials are described.

19

20   **4.   BRIEF DESCRIPTION OF DRAWINGS**

21

22   Figures 1a and 1b show, in overview, the operation of a normally white, 90°

23   twisted nematic liquid crystal display.

24

25   Figure 2 depicts a coordinate system that is used to specify component

26   orientations in the description of this invention.

27

1   Figure 3 is a cross-sectional schematic view of a 90° twisted nematic,

2   transmissive type normally white liquid crystal display.

3   Figure 4 is a plot of the tilt angle of the director (in degrees along the vertical

4   axis) as a function of position (as a fraction of the depth along the horizontal axis) in

5   a 90° twisted nematic liquid crystal cell.

6

7   Figure 5 is a related plot for the cell shown in Figure 4, depicting the twist

8   angle of the liquid crystal molecules as a function of their position in the cell.

9

10   Figure 6 is a plot of calculated brightness vs. voltage electrooptic curves at a

11   variety of horizontal viewing directions for a typical twisted nematic display without

12   the benefit of O-plate gray scale compensation.

13

14   Figure 7 is a plot of calculated brightness vs. voltage electrooptic curves at a

15   variety of vertical viewing directions for a typical twisted nematic display without the

16   benefit of O-plate gray scale compensation.

17

18   Figure 8 is an illustration of the viewer's perspective relative to the average

19   director orientation of a liquid crystal display.

20

21   Figure 9 is a plot of calculated brightness versus voltage electrooptic curves at

22   a variety of horizontal viewing directions for a typical twisted nematic display with

23   the benefit of O-plate gray scale compensation.

24

25   Figure 10 is a plot of calculated brightness versus voltage electrooptic curves

26   at a variety of vertical viewing directions for a typical twisted nematic display with

27   the benefit of O-plate gray scale compensation.

28

1   Figure 11 is a cross-sectional view of a normally white, twisted nematic liquid

2   crystal display in accordance with the invention.

3

4   Figure 12 is a cross-sectional schematic view of one embodiment of a

5   twisted/splayed O-plate compensator stack produced by polymerization of nematic

6   liquid crystal monomers.

7

8   Figure 13 is a cross-sectional schematic view of one embodiment of a twisted

9   O-plate compensator stack produced by polymerization of smectic C liquid crystal

10   monomers.

11

12   Figure 14 is a cross-sectional schematic view of one embodiment of a

13   multilayer twisted/splayed O-plate compensator stack produced by polymerization of

14   nematic liquid crystal monomers.

15

16   **5.   DETAILED DESCRIPTION OF A SPECIFIC EMBODIMENTS**

17

18   Illustrative embodiments of the invention are described below as they might be

19   implemented using polymeric liquid crystalline thin films to create a twisted and/or

20   splayed O-plate compensator. In the interest of clarity, not all features of an actual

21   implementation are described in this specification. It will of course be appreciated

22   that in the development of any such actual implementation (as in any development

23   project), numerous implementation-specific decisions must be made to achieve the de-

24   velopers' specific goals and subgoals, such as compliance with system- and business-

25   related constraints, which will vary from one implementation to another. Moreover,

26   it will be appreciated that such a development effort might be complex and time-

27   consuming, but would nevertheless be a routine undertaking of device engineering for

28   those of ordinary skill having the benefit of this disclosure.

5.1 Introduction

Figure 11 shows an illustrative embodiment of a liquid crystal display (LCD) system in accordance with the invention, that uses a single twisted and/or splayed O-plate compensator **1100** disposed between a polarizer **1105** and a liquid crystal layer **1110**. The O-plate layer **1100** comprises birefringent liquid crystal polymer layer having an optical symmetry axis **1120** oriented, on average, at a tilt angle **1125**, relative to the surface of the liquid crystal polymer layer **1110**, of approximately 20° to 80°. Alternatively, the O-plate layer could be located between liquid crystal layer **1110** and an analyzer **1115**, or in both locations. More details on the structure of the twisted and/or splayed O-plate layer are given below.

The decision as to where to place the O-plate compensator is purely a design choice and is, generally, based on the optical requirements of the display being compensated and on the manufacturing and cost constraints of the display system.

In general, O-plate compensators may also include A-plates and/or negative C-plates as well as O-plates. Twisted/splayed O-plate compensators may contain both twisted/splayed O-plates and simple O-plates. As is well known in the art, an A-plate is a birefringent layer with its extraordinary axis (i.e., its c-axis) oriented parallel to the surface of the layer. Its a-axis is thus oriented normal to the surface (parallel to the direction of normally incident light), leading to its designation as an A-plate. A-plates may be fabricated by the use of uniaxially stretched polymer films, such as polyvinyl alcohol, or other suitably oriented organic birefringent materials.

5.2   Nematic Embodiment

Another illustrative embodiment, shown in Figure 12, includes a rigid glass substrate **1200**, an alignment layer **1205**, a polymerized pretilt nematic liquid crystal layer **1207**, an alignment/pretilt layer interface **1205/1207**, a polymerized nematic liquid crystal monomer layer **1210**, a pretilt/liquid crystal layer interface **1207/1210** and a nematic/air interface **1212**. The nematic material in the layer **1210** has been doped with a chiral dopant to yield a cholesteric pitch approximately 12 times the layer thickness, yielding a twist angle of approximately 30 degrees in the layer **1210**. The liquid crystal layers are deposited in the form of polymerizable nematic monomer compounds doped with approximately 0.5% of Igracure-651, a photoinitiator.

The alignment layer **1205** is produced by coating a surface of the substrate **1200** with a polyimide material that produces a liquid crystal pretilt angle of from 1° to 10°in the layer **1207** at the alignment/pretilt layer interface **1205/1207**. The alignment material is then rubbed so as to produce uniformly tilted alignment in the desired azimuthal orientation in the layer **1207**.

A thin film of liquid crystal monomer is applied to the alignment layer **1205** using the technique of spin coating from a solution in an inert solvent. Other methods of coating the nematic material such as, for example, dip or slot-die coating can be used as well. The solution coated onto the surface of the alignment layer **1205** may contain prepolymerized liquid crystal side-chain polymers added as a viscosity modifier to improve coating wetting characteristics. In addition, the solution should contain a photoinitiator as stated above.

After the nematic film has been applied to the alignment layer **1205**, the solvent is driven off at elevated temperature producing the pretilt layer **1207**. The

1   temperature of the pretilt layer **1207** is adjusted so as to produce the desired nematic

2   phase in the layer **1207** and the desired tilt angle at the **1207/1210** interface. The

3   liquid crystal film is then illuminated with ultraviolet light (actinic radiation) at a

4   wavelength of approximately 360 nanometers with a total exposure sufficient to

5   polymerize the monomer to liquid crystal polymer film, thereby preserving the order

6   of the liquid crystal phase of the layer **1207** and the desired tilt angle at the

7   **1207/1210** interface.

8   The purpose of the liquid crystal pretilt layer **1207** is to provide a high pretilt

9   alignment layer for the liquid crystal monomer used to produce the actual

10   compensator layer **1210**. If the pretilt layer **1207** is thick enough, the pretilt angle of

11   the material at the surface of the layer **1210** will be dictated by the nematic/air tilt

12   angle of the material at the surface of the layer **1207**. After the application of the

13   liquid crystal layer **1210**, the nematic/air interface of the layer **1207** becomes the

14   pretilt/liquid crystal interface **1207/1210**. The nematic material in the layer **1207**

15   undergoes an incremental tilting, referred to as a continuous splay/bend deformation,

16   from the low tilt angle at the **1205/1207** interface up to the desired tilt angle at the

17   **1207/1210** interface. For the layer **1207**, the difference between the tilt angle at the

18   **1205/1207** interface and the tilt angle at the **1207/1210** interface is referred to as the

19   splay angle. The pretilt layer **1207** should be sufficiently thin, approximately 100

20   nm., when compared to the thickness of layer the **1210**, approximately 1 μm., such

21   that its optical retardation will be insignificant as compared to the overall retardation

22   of the compensator stack.

23

24   Other possible alignment layer materials could be substituted for the layers

25   **1205** and **1207** to give the required 30° pretilt angle and azimuthal alignment for the

26   liquid crystal layer **1210**. Such materials could include, for example, mixtures of

27   homogenous and homeotropic alignment materials that are then rubbed.

28

1   After the layer **1207** has been prepared, another layer of nematic monomer

2   solution is deposited on its surface in a manner entirely analogous to the original

3   deposition of the layer **1207**. After the solvent has been driven off and the material

4   polymerized with UV irradiation, this material constitutes layer **1210**. Other methods

5   for polymerizing thin monomer films well known in the art could be used.

6

7   The material used to prepare the layer **1210** is similar to that in **1207** with a

8   few exceptions. The material in the layer **1210** has been doped with a chiral material

9   as described above so as to produce an approximately 30° twist of the azimuthal

10   orientation of the nematic optical symmetry axis (extraordinary axis). This variation

11   in azimuthal orientation occurs about an axis normal to the layer **1210** from top to

12   bottom through the layer **1210**. The twisted and splayed structure of the layer **1210** is

13   represented by the liquid crystal side chains or moieties **1220**. The variation in the

14   orientation of the optical symmetry axis of the layer **1210** is represented by the arrows

15   **1225** projected from the moieties **1220**. As can be seen from Figure 12, the optical

16   symmetry axis varies through the layer **1210** according to the tilted and azimuthal

17   orientation of the moieties **1220** of the layer **1210**.

18

19   In this particular embodiment, the material used to produce the layer **1210** has

20   been chosen to have a tilt angle of 60° at the nematic/air interface **1212** (the 30°

21   pretilt angle at the **1207/1210** interface plus a 30° splay angle through the layer

22   **1210**). The solution concentration of the nematic monomer, concentration of

23   prepolymerized nematic polymer, and the deposition parameters are selected such that

24   the layer **1210** is of the proper thickness to provide the required retardation value, on

25   the order of 1 μm. A splayed/twisted O-plate layer prepared in this way will have a

26   varying optical symmetry axis with a splay angle of 30°, a twist angle of 30°, and an

27   average tilt angle of 45°.

28

5.3   Smectic C Embodiment

3   An alternative embodiment is shown in Figure 13. As before, the
4   compensator system comprises a rigid glass substrate **1300**, an alignment layer **1305**,
5   a polymerized liquid crystal layer **1310**, a liquid crystal/alignment layer interface
6   **1305/1310**, and a liquid crystal/air interface **1315**. In this embodiment, however, the
7   polymerized liquid crystal layer **1310** has a smectic C phase and a smectic C
8   intralayer tilt angle of 45°. As such, the desired intralayer tilt angle (45°) of the
9   liquid crystal layer **1310** remains constant through the layer **1310**.

11   A liquid crystal material with a smectic C to nematic phase transition rather
12   than a smectic C to smectic A phase transition is preferred because such materials
13   tend to have large, in the range of 10° to 45°, smectic C intralayer tilt angles.

15   As in the nematic embodiment, an alignment layer **1305** is produced on the
16   surface of the substrate **1300**. In one embodiment, the alignment layer **1305** material
17   is a thin film of silicon monoxide, SiO_x, obliquely deposited at a polar angle of
18   approximately 60° and overcoated with a thin film of egg lecithin, a homeotropic
19   alignment material. This alignment layer **1305** produces a liquid crystal pretilt angle
20   for nematic materials of approximately 80° and a uniform azimuthal direction of the
21   liquid crystal director which is determined by the azimuthal SiO_x deposition angle.

23   Next, a thin film of polymerizable liquid crystal monomer is laid down on the
24   alignment layer **1305** using techniques detailed in the nematic embodiment. The
25   liquid crystal monomer is doped with a chiral material such that in its smectic C
26   phase it will have a chiral pitch approximately 12 times the thickness of the layer
27   **1310**, yielding a twist angle of approximately 30 degrees through the layer **1310**.
28   After the solvent has been removed, the temperature of the monomer film is raised

1   high enough to transform it into the nematic phase. The nematic phase then adopts a

2   uniform pre-tilt angle of 80° at the liquid crystal/alignment layer interface **1305/1310**.

3   The temperature is then slowly decreased, eg., at a rate of approximately 0.1°C per

4   second, transforming the liquid crystal film into its smectic C phase.

5

6   This process forms smectic C layers parallel to the surface of the alignment

7   layer **1305** with the molecules initially adopting a smectic C intralayer tilt angle of

8   approximately 0°. As the temperature of the film is lowered further through its

9   smectic C temperature range, the smectic C intralayer tilt angle increases. (The

10   azimuthal direction of the molecules is determined by the azimuthal SiO_x deposition

11   angle.) At a temperature just above the material's melting point, the smectic

12   intralayer tilt angle reaches a maximum value of approximately 45°. Furthermore, in

13   a smectic C material, the polar tilt angle at the liquid crystal/air interface **1312** does

14   not influence the tilt angle of the bulk liquid crystal material in the layer **1310**.

15   Various other ways to form smectic layers parallel to the alignment layer will be

16   recognized by those skilled in the art.

17

18   As stated above, the liquid crystal monomer is doped with a chiral material to

19   produce an approximately 30° twist of the azimuthal orientation of the liquid crystal

20   optical symmetry axis (extraordinary axis). This variation in azimuthal orientation

21   occurs about an axis normal to the layer **1310** from top to bottom through the layer

22   **1310**. The azimuthal orientation of moieties **1320** at the liquid crystal/air interface

23   **1312** is determined by a combination of the azimuthal orientation of the liquid crystal

24   at the liquid crystal/alignment layer interface **1305/1310**, the pitch of the chiral helix

25   in the smectic C material, and the smectic C film layer thickness. The tilted helical

26   structure of the smectic material in the layer **1310** is represented by the moieties

27   **1320**. The variation in the orientation of the optical symmetry axis of the layer **1310**

28   is represented by the arrows **1325** projected from the moieties **1320**. As can be seen

1   from Figure 13, the optical symmetry axis varies through the layer **1310** according to

2   the tilted and azimuthal orientation of the moieties **1320** of the layer **1310**.

3

4   Upon obtaining the desired intralayer tilt angle in the liquid crystal film and

5   the desired azimuthal orientation, the liquid crystal monomer film is irradiated with

6   ultraviolet light that is sufficient to polymerize the monomer to a polymeric film **1310**

7   in which the order of the smectic liquid crystal is preserved., typically 4 - 10 J/cm^2.

8   Other polymerization techniques for thin films are well known in the art and may also

9   be used. The result of this process is a thin film or liquid crystal layer **1310** of liquid

10   crystal polymer that is positively birefringent and has an optical symmetry axis that is

11   oriented at a polar tilt angle of approximately 45° with a twist angle of approximately

12   30°.

13

14   5.4   Multilayer Embodiment

15

16   A further illustrative liquid crystal display system, see Figure 14, includes a

17   rigid glass substrate **1400**, an alignment layer **1405**, polymerized nematic liquid

18   crystal pretilt layer **1410**, polymerized nematic liquid crystal layers **1415, 1420, 1425,**

19   and **1430;** a liquid crystal/alignment layer interface **1405/1410**, liquid crystal/liquid

20   crystal interfaces **1410/1415, 1415/1420, 1420/1425,** and **1425/1430;** and a liquid

21   crystal/air interface **1435**.

22

23   The alignment layer **1405**, the pretilt layer **1410** and the liquid crystal layer

24   **1415** are produced by methods identical to layers **1205, 1210,** and **1215** in the

25   nematic embodiment above with the following exceptions. The liquid crystal in the

26   pretilt layer **1410** is chosen to produce a tilt angle of approximately 40° at the

27   **1410/1415** interface after the liquid crystal layer **1415** is applied. As in the nematic

28   embodiment above, the function of the layer **1410** is to increase the pretilt of the layer

1 1415 to 40° without altering the azimuthal orientation of the moieties **1416** in the

2 layer **1415**. The liquid crystal in the layer **1415** is chosen to produce a tilt angle of

3 50° at the **1415/1420** interface after it is polymerized, thereby yielding a splay angle

4 of approximately 10° through the layer **1415**.

5

6 The liquid crystal in the layer **1415** is also doped with a chiral additive so as

7 to have a left handed cholesteric pitch of 24 times the layer thickness of the layer

8 **1415**, yielding an approximately 15° twist of the azimuthal orientation of the nematic

9 optical symmetry axis (extraordinary axis) through the layer **1415**. This variation in

10 azimuthal orientation occurs about an axis normal to the layer **1415** from top to

11 bottom through the layer **1415**. The twisted and splayed structure of the layer **1415** is

12 represented by the liquid crystal side chains or moieties **1416**. The variation in the

13 orientation of the optical symmetry axis of the layer **1415** is represented by the arrows

14 **1417** projected from the moieties **1416**. As can be seen from Figure 14, the optical

15 symmetry axis of the layers **1415**, **1420**, **1425** and **1430** (represented by arrows **1417**,

16 **1423**, **1427** and **1433**) vary through the respective layers **1415**, **1420**, **1425** and **1430**

17 according to the tilted and azimuthal orientation of the respective moieties **1416**,

18 **1422**, **1426** and **1432** of the respective layers **1415**, **1420**, **1425** and **1430**.

19

20 After the layer **1415** has been polymerized by irradiation with UV light, the

21 layer **1420** is applied over it. The layer **1415** functions to align layer **1420** to the

22 proper azimuthal and pretilt (50°) orientations at the **1415/1420** interface in a manner

23 analogous to the pretilt layer **1410** at the interface **1410/1415**. The liquid crystal in

24 the layer **1420** is doped with a chiral additive so as to have a right handed cholesteric

25 pitch of 24 times the thickness of the layer **1420**. As such, the layer **1420** will have a

26 twist structure equal in magnitude (15°) yet opposite in sense to that in the layer

27 **1415**. Additionally, the layer **1420** will have a splay angle (10°) equal in magnitude

1   to the splay angle of the layer **1415** but opposite in sign, thereby producing a 40° tilt

2   angle in the layer **1420** at the interface **1420/1425**.

3

4   In this particular embodiment, the layer **1415** is identical to the layer **1425**,

5   and layer **1420** is identical to layer **1430**. The present invention, however,

6   encompasses a multilayer embodiment in which the magnitude and sign of the tilt,

7   splay and/or twist orientations of the successive and/or alternating layers are different

8   in magnitude and/or in sign. Each successive layer is deposited over the preceding

9   layer after the preceding layer has been cured with UV radiation. Each succeeding

10   layer can be azimuthally aligned and pretilted at the interface by the preceding layer.

11   Other methods of polymerizing the succeeding layers may also be used. These could

12   include thermal cure and other irradiation techniques.

13

14   The purpose of producing a layered alternating splay/twist O-plate structure as

15   is described in this embodiment is to yield a compensator which has a biaxial nature,

16   but which has minimum twisting power for polarized light which transits the

17   compensator stack.

18

19   5.5   Possible Variations

20

21   For each of the previous illustrative embodiments, a number of variations are

22   possible and would be obvious to one skilled in the art of liquid crystal display

23   devices. For example, other possible substrate materials could include non-

24   birefringent polymer films. The polymerizable liquid crystal monomer material may

25   include, as a constituent, molecules that contain two reactive functional groups and

26   therefore can act as cross-linking agents. Other polar tilt angles at the liquid

27   crystal/alignment layer interface can be achieved by suitable selection of reactive

28   liquid crystals, modification of the alignment materials, rubbing conditions, etc.

1 Furthermore, a non-reactive liquid crystal material can be combined with the

2 polymerizable liquid crystal. The resulting liquid crystal polymer film would then

3 have the properties of a plastic or gel. The liquid crystal material could also contain

4 a polymer, liquid crystal polymer, or oligomer that increases the viscosity of the

5 liquid crystal mixture and improves the film forming properties thereof.

6

7 Additionally, the various embodiments have been described above with specific

8 pretilt, splay and twist orientations and/or angles, but the present invention is not

9 limited to specific angles or orientations. Finally, the multilayer embodiment has

10 been specifically described with nematic layers but the multilayer embodiment can be

11 of multiple smectic C layers.

12

13 ## 6. BIBLIOGRAPHY

14

15 a. Clerc et al., U.S. Patent No. 4,701,028.

16 b. Kahn, The Molecular Physics of Liquid-Crystal Devices, Physics Today, Page

17 66, May 1982.

18 c. Macleod, Structure-related Optical Properties of Thin Films, J. Vac. Sci.

19 Technol. A, Volume 4, No. 3, Pages 418-422, 1986.

20 d. Motohiro and Taga, Thin Film Retardation Plate by Oblique Deposition, Appl.

21 Opt., vol. 28, No. 13, Pages 2466-2482, 1989.

22 e. Yeh et al., "Compensator for Liquid Crystal Display Having Two Types Of

23 Layers With Different Refractive Indices Alternating", U.S. Patent No.

24 5,196,953.

25

26

27 It will be appreciated by those of ordinary skill having the benefit of this dis-

28 closure that numerous variations from the foregoing illustration will be possible with-

1   out departing from the inventive concept described herein. Accordingly, it is the

2   claims set forth below, and not merely the foregoing illustrative embodiments, which

3   are intended to define the exclusive rights claimed in this application program.